UNIVERSIDADE DE SÃO PAULO
FACULDADE DE ODONTOLOGIA DE BAURU

BRUNNA MOTA FERRAIRO

Comparison of marginal adaptation and internal fit of monolithic lithium disilicate crowns produced by four CAD-CAM systems

Comparação da adaptação marginal e do espaço interno de coroas monolíticas de dissilicato de lítio confeccionadas por quatro sistemas CAD/CAM

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“Mas na profissão, além de amar tem de saber.

E o saber leva tempo pra crescer.”

Rubem Alves

ABSTRACT

ABSTRACT

Comparison of marginal adaptation and internal fit of monolithic lithium disilicate crowns produced by four CAD/CAM systems

Statement of the problem. The marginal adaptation and internal space of monolithic crowns are essential items for their longevity. With the variety of CAD-CAM systems available, evaluating the accuracy of its production is of great clinical interest.
Purpose. Evaluating the marginal adaptation and internal fit of monolithic lithium disilicate crowns produced by four different CAD-CAM systems.
Material and methods. CAD-CAM systems were selected: Ceramill (Ceramill Motion 2), Cerec (Cerec 3), EDG (CAM5-S1 SmartDent) and Zirkonzahn (M5 Heavy). An artificial lower first molar was prepared for a full crown, duplicated in plaster, scanned and the crown was designed following standardized parameters. Ten lithium disilicate crowns (IPS e.max CAD) per group were milled. The crowns were filled with low viscosity silicone and seated on the prepared tooth. The pellicle formed was scanned by the SkyScan 1076 micro-CT system and subsequently embedded in heavy body silicone, sectioned and captured by means of a stereomicroscope at 50x magnification, according to replica technique. Internal and marginal adaptation were measured in the micro-CT and in stereomicroscope images. Two-way ANOVA followed by Tukey's test were used for statistical analysis (α=.05). A uniformity index (UI) to describe the internal space of the crown was idealized and submitted to the Kruskal-Wallis one-way analysis of variance on ranks and Tukey's test (α=.05).
Results. Marginal adaptation presented values ranging from 48,2 ± 19,6 µm to 133,0 ± 71,5 µm. Highest averages were found for the axial (170,1 ± 38,2 µm Zirkonzahn group/micro-CT) and occlusal (229,4 ± 49,0 µm Cerec group/micro-CT) areas. Zirkonzahn group showed the UI closest to the ideal.
Conclusion. The marginal adaptation and internal fit parameters of the 4 tested CAD-CAM systems were within clinically acceptable levels.

Key words: Dental Marginal Adaptation. Computer-Aided Design. Crowns. Ceramics.

Resumo

RESUMO

Comparação da adaptação marginal e do espaço interno de coroas monolíticas de dissilicato de lítio confeccionadas por quatro sistemas CAD/CAM

Afirmação do problema. A adaptação marginal e o espaço interno das coroas monolíticas são itens essenciais para sua longevidade. Com a variedade de sistemas CAD-CAM disponíveis, avaliar a precisão de sua produção é de grande interesse clínico.

Finalidade. Avaliar a adaptação marginal e o espaço interno de coroas monolíticas de dissilicato de lítio produzidas por quatro sistemas CAD-CAM diferentes.

Material e métodos. Os sistemas CAD-CAM foram selecionados: Ceramill (Ceramill Motion 2), Cerec (Cerec 3), EDG (CAM5-S1 SmartDent) e Zirkonzahn (M5 Heavy). Um primeiro molar inferior artificial foi preparado para coroa total, duplicado em gesso, digitalizado e a coroa foi projetada seguindo parâmetros padronizados. Dez coroas de dissilicato de lítio (IPS e.max CAD) foram fresadas por grupo. As coroas preenchidas por silicona de adição leve foram assentadas sobre o preparo dentário. A película formada foi escaneada através do micro-CT SkyScan 1076 e posteriormente incluída em silicona de adição pesada, seccionada e capturada utilizando o estereomicroscópio com magnificência de 50x, de acordo com a técnica da réplica. A adaptação marginal e o espaço interno foram mensurados pelas imagens do micro-CT e estereomicroscópio. ANOVA 2 fatores seguido do teste de Tukey seguido de teste de Tukey foram utilizados para a análise estatística (α=.05). O índice de uniformidade (IU) que descreve o espaço interno da coroa foi idealizado e submetido ao teste de associação de Kruskal-Wallis e teste de Tukey (α=.05).

Resultados. A adaptação marginal apresentou valores que variaram de 48,2 ± 19,6 µm a 133,0 ± 71,5 µm. Médias mais altas foram encontradas para as regiões axial (170,1 ± 38,2 µm grupo Zirkonzahn/micro-CT) e oclusal (229,4 ± 49,0 µm Cerec/micro-CT). O grupo Zirkonzahn apresentou o IU mais próximo do ideal.

Conclusão. A adaptação marginal e o espaçamento interno para os 4 sistemas CAD-CAM avaliados estão de acordo com os níveis clinicamente aceitáveis.

Palavras chave: Adaptação Marginal Dentária. Projeto Auxiliado por Computador. Coroas. Cerâmica.

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1 INTRODUCTION

Computer-aided design and computer-aided manufacturing (CAD/CAM) technology were idealized with the aim of recovering and maintaining the oral function and health of patients in a standardized, reproducible, and efficient way.[1] It also improves the average quality of prostheses adaptation compared with that obtained with conventional manufacturing methods.[2]

The use of this technology in dentistry was proposed in the 1970s in the United States by Bruce Altschuler and in Europe with François Duret (German), Werner Mörmann and Marco Brandestini (Swiss).[3] In 1987, Duret introduced the first complete CAD/CAM system for dentistry[4], using a numerically controlled milling machine. Because of its complexity and high cost, it was not a successful project, however it featured as a start point for the first commercially available dental CAD/CAM system, CEREC.[5]

Developed by the dentist Mörmann and the electrical engineer Brandestini, the acronym CEREC stands for “Chairside Economical Restoration Esthetic Ceramic”. In 1985, they performed the first chairside inlay using a combination of their optical scanner and milling device. At that time, the main obstacle was the high costs associated with the requirements for computer support. In the mid-1990s, the evolution of personal computers provided the rapid development of 3-D scanning and CAD technology in dentistry.[4] Since then, their development has been constantly making progresses.[6]

Nowadays, a great variety of CAD-CAM systems are available on the market and there are always new others being developed. The main goal is the solution of the three major challenges in indirect restorations: 1) to make production easier, faster and more accurate; 2) to guarantee adequate strength, especially for posterior teeth; and 3) obtaining a natural appearance.[7]

The expensive milling tools, time-consuming processes, waste products, and wear of equipment are some disadvantage points.[8] Moreover, each step in the CAD/CAM chain is of utmost importance and the fit of CAD/CAM restorations could be affected by scanner precision, transformation of the scanning data into 3-dimensional models, and precision of the milling machine.[9,10]

Over the years, because of the market appeal, the industry have improved the quality of scanned images, the efficiency of milling, the use of occlusal concepts, with the introduction of virtual articulator software, and the development and usability of new materials.[11]

Dental ceramics represent a wide variety of materials with an increased range of properties and indications. New high-strength ceramics, for example, zirconia, cannot be managed using conventional dental processing methods because of its high hardness even in pre-sintered phase, increasing the need for an automatized system. In the last three decades, it could be observed a trend to use ceramic materials, in order to meet the demands of patients and professionals for excellence in aesthetics, biocompatibility and durability.[12,13] This trend tends to increase; it has been estimated that by the year 2017, approximately 42% of fixed dental restorations will use ceramic materials.[12]

Monolithic crowns made of lithium disilicate glass ceramic combine the most desirable features in dental ceramics. They have shown improved strength compared to earlier glass ceramics and excellent aesthetic properties.[14] Compared to the opaque yttria-stabilized tetragonal zirconia polycrystal (Y-TZP), another high-strength dental ceramic, lithium disilicate presents esthetic appearance and high translucency, easily matching natural teeth.[15] An additional advantage is that processing[16,17] and clinical aspects[18] of this material have been well documented. While these characteristics grant its indication for full crowns[18], CAD/CAM manufacturing have made them very popular.[19]

Ceramic restorations that follow the correct protocols and procedures have a minimum longevity of 5 years, with low complication rates. The most common complications are secondary caries, endodontic problems, ceramic chipping and loss of retention.[20] The clinical performance of a ceramic crown is complex and depends on many factors controlled by the clinician, the dental technician and the patient.[21] Tooth preparation characteristics, crown shape and thickness, laboratory processing methods, elastic modulus of the restoration material, marginal and internal fit and the post operative control are some of the factors that influence prosthesis longevity.[22-24]

Marginal and internal precision are believed to be the most important criteria for the clinical quality and success of all-ceramic crowns. Several studies highlight that poor adaptation might lead to marginal microleakage, increased plaque retention, marginal discoloration and secondary caries or onset of periodontal disease.[10,19,25-30] These outcomes may be attributed to an exaggerated exposure of the cement, that would increase the natural dissolution of the material and turn the region into a focus for bacterial infiltration, changing the composition of the subgingival microflora.[31]

On the other hand, some authors report that there is no clinical evidence of correlation between marginal fit and secondary caries or periodontal complications.[32-34] The ease in analyzing the margin of the prosthesis may be the reason for this being a parameter so assessed and therefore associated with one of the most common problems of prosthesis failure: secondary caries. CAD/CAM systems manufacturers would tend to follow this concern line only to satisfy the desires of the professionals.[32]

Despite the divergence among authors, even if marginal misfits do not culminate in biological damage, clearly they cannot be disregarded. A variety of clinical trials and *in vitro* studies on this subject has been conducted and no consensus exists on a clinically acceptable cement space. An acceptable marginal fit-discrepancy has been suggested as 120 µm at the most[35], whereas other studies have reported a range from 50 to 150 µm.[36]

Another point to be investigated is the measure of the space between the inner surface of the crown and the surface of the prepared tooth, classified as internal space. It is a clinically relevant topic and can affect the strength of a crown-cement system.[37] Variations of this parameter may occur due to the marginal preparation design or the die relief[38]; the crown fabrication technique; variations in powder/liquid ratio of the cement; the pressure applied during cementation and cement film thickness.[39] A uniform fit collaborates with the retention and the resistance of the crown, providing an appropriate cement space.[40] The load required for fracturing of feldspathic porcelain crowns, for example, decreases as the thickness of the resin cement layer increases. The polymerization shrinkage of a thick resin cement layer produces harmful stresses and their low modulus of elasticity, compared to ceramics, make it a more compliant substrate when subjected to load, resulting in radial cracks of the ceramic material.[32,41]

Internal space can vary either within a single system or between different CAD/CAM systems. Variations between 24 µm to 634 µm on the same system[42] and misfits as larger as 1316 µm[43] have been reported. The acceptable internal space, based on literature reports, range from 50 µm to 500 µm. This variability between acceptable results should still be extended many times above and below the expected values in order to completeness and to accentuate trends.[32] Despite the CAD software requires the selection of a desirable cementation space, the results seem not to be as precise as it would be expected.[32,40,43]

Certainly, the CAD/CAM industry is aware of the necessity of appropriate adjustments and makes constantly efforts to achieve favorable results. Evaluate the variation between the systems is important in order to verify the quality and accuracy that is delivered.

The purpose of this *in vitro* study was to compare the marginal adaptation and internal fit of monolithic lithium disilicate crowns produced by four different CAD-CAM systems, using replica technique and micro-CT technology.

The study hypotheses are that the evaluated CAD/CAM systems can deliver lithium-disilicate single crowns with comparable marginal adaptation and internal fit and both techniques are effective for measuring marginal and internal space.

2 Article

2 ARTICLE

The article presented in this Dissertation was written according to The Journal of Prosthetic Dentistry instructions and guidelines for article submission (Annex A).

COMPARISON OF MARGINAL ADAPTATION AND INTERNAL FIT OF MONOLITHIC LITHIUM DISILICATE CROWNS PRODUCED BY FOUR CAD-CAM SYSTEMS

ABSTRACT

Statement of the problem. The marginal adaptation and internal space of monolithic crowns are essential items for their longevity. With the variety of CAD-CAM systems available, evaluating the accuracy of its production is of great clinical interest.
Purpose. Evaluating the marginal adaptation and internal fit of monolithic lithium disilicate crowns produced by four different CAD-CAM systems.
Material and methods. CAD-CAM systems were selected: Ceramill (Ceramill Motion 2), Cerec (Cerec 3), EDG (CAM5-S1 SmartDent) and Zirkonzahn (M5 Heavy). An artificial lower first molar was prepared for a full crown, duplicated in plaster, scanned and the crown was designed following standardized parameters. Ten lithium disilicate crowns (IPS e.max CAD) per group were milled. The crowns were filled with low viscosity silicone and seated on the prepared tooth. The pellicle formed was scanned by the SkyScan 1076 micro-CT system and subsequently embedded in heavy body silicone, sectioned and captured by means of a stereomicroscope at 50x magnification, according to replica technique. Internal and marginal adaptation were measured in the micro-CT and in stereomicroscope images. Two-way ANOVA followed by Tukey's test were used for statistical analysis (α=.05). A uniformity index (UI) to describe the internal space of the crown was idealized and submitted to the Kruskal-Wallis one-way analysis of variance on ranks and Tukey's test (α=.05).
Results. Marginal adaptation presented values ranging from 48,2 ± 19,6 µm to 133,0 ± 71,5 µm. Highest averages were found for the axial (170,1 ± 38,2 µm Zirkonzahn group/micro-CT) and occlusal (229,4 ± 49,0 µm Cerec group/micro-CT) areas. Zirkonzahn group showed the UI closest to the ideal.
Conclusion. The marginal adaptation and internal fit parameters of the 4 tested CAD-CAM systems were within clinically acceptable levels.

INTRODUCTION

Marginal and internal adaptation is believed to be one of the most important conditions for the clinical longevity and success of restorations. Imperfect margins might lead to marginal microleakage, discoloration and enhanced plaque retention, which can cause secondary carie and/or onset of periodontal disease.[1-8] The internal fit is also an important factor since it is directly associated with the retention and resistance of restoration.[9] Providing an appropriate cement space is essential for a homogenous stress distribution under masticatory loads[10] while wide resin cement thickness reduces the load required for the occurrence of fracture.[11,12]
Computer-aided design and computer-aided manufacturing (CAD/CAM) technology were idealized with the aim of recovering and maintaining the oral function and health of patients in a standardized, reproducible, and efficient way.[13] It also improves the average quality of prostheses adaptation compared with that obtained with conventional manufacturing methods [14] by reducing the number of manual steps in the manufacturing process, which in turn may reduce errors in the final restoration.[15-19]

Nowadays, several CAD-CAM systems is available on the market and there are always new others being developed. Internal space and marginal gap can vary either within a single system or between different CAD/CAM systems. Despite the CAD software's need to select of a desirable parameter of internal space or cement thickness, apparently the milling or sintering units do not deliver the expected adaptation.[9, 11,23]

A variety of clinical trials and *in vitro* studies about this subject has been conducted and there is no consensus on a clinically acceptable cement space. An acceptable marginal fit-discrepancy has been suggested as 120 µm at the most [20], whereas other studies have reported a range from 50 to 150 µm.[21] For internal adaptation a variation between 24 µm to 634 µm on the same system[22] and misfits as larger as 1316 µm[23] have been reported. The acceptable internal space, based on literature reports, range from 50 µm to 500 µm.[11]

Monolithic crowns made of lithium disilicate glass ceramic became very popular.[4] This material combine the most desirable features in dental ceramics: high flexural strength and the excellent aesthetic properties.[24] It can be processed as a pressed or milled restorations that can be individualized by external characterization, covering all kinds of single tooth restorations from inlays and partial crowns, up to full mouth rehabilitation.[25]

The increased demand makes CAD-CAM industry be aware, produces with appropriate adjustments and makes constantly efforts to achieve favorable results. However, evaluating the variation between systems is important in order to verify the quality and accuracy of the delivered restorations.

The purpose of this *in vitro* study was to compare the marginal adaptation and internal fit of monolithic lithium disilicate crowns produced by four different CAD-CAM systems, using replica technique and micro-CT technology.

The study hypotheses are that (1) the evaluated CAD/CAM systems can deliver lithium-disilicate single crowns with comparable marginal adaptation and internal fit and (2) both techniques are effective for measuring marginal and internal space.

MATERIALS AND METHODS

Tooth preparation and cast fabrication

An artificial lower first molar positioned in a mannequin was prepared for a complete crown. The preparation comprised a 2.0 mm occlusal reduction, 1.5 mm axial reduction and a 1.2 mm shoulder finish line with rounded internal angles.[26]

The prepared molar received an impression with polyvinyl siloxane material (Express; 3M ESPE, St Paul, USA) using the double impression technique and the plaster model was made with type IV special CAD/CAM stone (CAM-base; Dentona AG, Dortmund, Germany). The model was digitalized and the crown design was provided following the standardized parameters. For each group the complete system was used: scanner, design software and milling unit.

After the impression, the prepared tooth was removed from the mannequin and included in an acrylic base (Fig. 1). In order to facilitate handling during the subsequent steps of the experiment and named as master model.

Crowns fabrication

Ten crowns per group were milled from lithium disilicate glass-ceramic blocks (IPS e.max CAD; Ivoclar-Vivadent, Amherst, NY), with minimum ceramic thickness of 2 mm (Fig. 2). A uniform 50 µm cement spacer was set and there were no internal grinding for corrections or adjustments for the fit of the crowns. As reference, a wax-up model was used to determine the occlusal anatomy.

Four CAD-CAM systems were selected and the groups named:

- CERAMILL - Ceramill Motion 2 (Amann Girrbach AG, Koblach, Austria)
- CEREC - Cerec 3 (Sirona Dental Systems GmbH, Bensheim, Germany)
- EDG - SmartDent CAM5-S1 (EDG Equipamentos e Controles Ltda; São Carlos, Brazil)

- ZIRKONZAHN - Milling Unit M5 Heavy (Zirkonzahn, South Tyrol, Austria)

After milling, crowns were sintered and glazed according to the manufacturer's instructions.

Micro-CT scanning

Micro-CT measurements of cement space were performed by x-ray microtomography. Each crown was seated on the master model with a light body silicone layer (Express™ VPS Impression Material; 3M ESPE Dental, Saint Paul, MN) representing cementation material (Fig. 3). A 50N load was applied using a load device and the excess of paste around the crown was wiped away before the final setting to avoid material tearing (Fig. 4). After polymerization, the crown was carefully removed (Fig. 5).

The pellicle of silicone positioned on the prepared tooth was scanned using a desktop X-ray microfocus CT scanner (SkyScan 1174v2; SkyScan, Kontich, Belgium). Images were acquired using 50 kV X-ray tube voltages, 800 μA anode current and voxel size of 16 μA. The specimens were scanned over 360 degrees (1 complete rotation) at 5 frames per rotation step of 0.38 degree. The average scanning time of each specimen was approximately 15 minutes.

After scanning, scans were reconstructed using NRecon v1.6.10 (SkyScan) software. Film thickness was volumetrically analyzed using CTscan v1.11.10.0 (SkyScan) software, individually for each crown. The SkyScan DataViewer 1.5.1.2 software can generate 3 views: coronal (x-z plane), sagittal (y-z plane), and transaxial (x-y plane) (Fig. 6). They were used to locate the mesiodistal and buccolingual positions of the crown in order to evaluate the measures.

Replica technique

A test device to standardize the replica's position and, consequently, the areas chosen for analysis, was made. After the micro-CT scanning, the master model with the light body silicone pellicle was seated on a test device filled with heavy body silicone (Express™ VPS Impression Material; 3M ESPE Dental, Saint Paul, MN) (Fig. 7). The model was removed after silicone polymerization (Figure 8) and then a portion of heavy body silicone was introduced to support the film of light body silicone (Figure 9).[27] Replicas were sectioned perpendicular to its surface with a blade into four parts determined with the assistance of the device: mesial, distal, facial and lingual areas (Figure 10).[28]

Gap measurements

All specimens were evaluated for marginal adaptation and internal fit using micro-CT and replica technique images.

Micro-CT measurements

CTAn software (Skyscan, Aartselaar, Belgium) was used to choose a region of interest, desired number of slices for the region selected and to perform the measurements. The center of the prepared tooth was located and provided a starting point for the measurements (Fig. 11). Measurements of marginal and internal space were performed at the center and both mesiodistal and buccolingual directions. As shown in the scheme, measurements were performed in other six slices 0.8 mm apart from each other in the mesiodistal and buccolingual directions (Fig. 12), resulting in seven measurements towards each direction. Consequently, the number of slices could be standardized for all specimens, and the same slice was analyzed for each crown. All measurements were performed by a single examiner. The presence of small radiographic artifacts precluded the use of any automatic tool.

Therefore, all measurements were taken manually, and the measuring points were standardized to minimize errors. Eighty-four measurements were taken for each specimen.

Replica technique measurements

Film thickness was captured by means of a stereomicroscope (MZ6, Leica, Wetzlar, Germany) at 50x magnification factor, with a built-in charge-coupled camera (Hitachi CCTV HV-720E, Hitachi, Tokyo, Japan). Image J image analysis software was used to measure the cementing agent space. The most external margin of the pellicle, the center of the axial wall and the occlusal surface were observed of each side of the crown in order to evaluate the measures (Figure 13).[29,30] Twelve measurements were taken for each specimen.

Uniformity index

Since crown internal space is important to the outcome of the restoration, a uniformity index (UI) was idealized to describe how uniform it is. The calculation of UI results from the division of the mean of the occlusal region by the mean of the axial region (UI= occlusal region mean/axial region mean). The closer the ratio is to 1 the more uniform the internal space is.

Statistical analysis

Each variable was analyzed descriptively as mean, 95% confidence interval, and range. Two-way analysis of variance (ANOVA) was used for comparison of means from the four experimental groups and the two methods of analysis at the 5% significance level. Pairwise between-group differences were assessed with the Tukey range test. Values obtained from uniformity index calculations were submitted to the Kruskal-Wallis one-way analysis of variance on ranks and Tukey’s test, at a significance level of 5%.

RESULTS

Tables 1 and 2 shows the descriptive data with mean and standard deviation for the studied groups. Regarding marginal fit, all systems presented values in accordance with the clinically acceptable by the literature. According to internal fit, the distribution of associations was heterogeneous, but the values of the occlusal fit were significantly higher. It is worth mentioning that the absolute values are mostly lower for replica techniques compared to micro-CT, what will be reviewed in the discussion.

Micro-CT and replica technique analysis were submitted to two-way analysis of variance (ANOVA) and showed statistical difference between groups for the factors *system* and *region* separately. However, there was interaction between them, which predominates, and Tukey test were applied separately for both techniques.

Since two methods were used for the analysis of adaptation, it was relevant to evaluate the correlation between them. Because of a methodological reason, the average of the measures were considered, since 28 measurements were taken at a particular region of a specimen on the micro-CT and only 8 measurements were taken to the replica technique for the equivalent area. Pearson's correlation coefficient was performed and it was statistically significant, showing a strong correlation between the methods ($p = 0{,}01$ and $r = 0{,}69$).

Values obtained from UI were submitted to the Kruskal-Wallis one-way analysis of variance on ranks and Tukey's test, at a significance level of 5%. This data is shown on Graphics 1 and 2. In general, the variability of the replica technique was lower than for micro-CT. However, for both analysis the Zirkonzahn group showed the UI closest to 1, i.e., the distribution of internal spacing is more uniform. It was followed by CEREC, EDG and Ceramill respectively.

DISCUSSION

Marginal adaptation and internal fit are considered the most important criteria for the longevity of all-ceramic crowns.[31] Most of the previous that evaluate this parameters was done using replica technique[28], a well-established methodology in the literature. However, this method have some limitations: the fit is measured at predefined points on each crown, which might not represent the overall accuracy[14,29,32]; indirect data acquisition[33,23] and also some errors during replication could occur, once very tight adaptations can lacerate the pellicle[34]; and difficulties with the specimen sectioning.[35,36]

In order to reduce the limitations, it has been proposed in this study the use of a device for standardization of the replica technique (Fig. 8). The inclusion of the light body silicone pellicle in a matrix of heavy body silicone in a standardized way, favored the slices made and consequently standardized the samples for posterior analysis. The measurements were performed at the marginal, axial and occlusal regions of each slice of the vestibular, mesial, distal and lingual tooth surfaces.[28] Previous studies revealed that no statistical difference exists between the measurements according to the tooth surfaces.[14] Therefore, data were grouped into regions in order to clarify the interpretation.

An acceptable marginal fit has been suggested as a maximum of 120 μm[20] in most studies, whereas others have been reported a range from 50 to 150 μm[21]. Boitelle et al.[14] in a recent systematic review reported that from 26 articles dealing with the adaptation of single crowns, the marginal adaptation ranged from 9.94 ± 4.18 μm to 308 ± 92 μm, but most studies have shown less than 80 μm. The medians of all four systems tested in the present study were in accordance with the average found in the literature and within clinically acceptable.

Considering absolute values, the Zirkonzahn group presented lower values for marginal fit (48.2 ± 19.6 μm). However, there was no statistical difference between Zirkonzahn, EDG and Cerec groups. Performing the same analysis inversely, the Ceramill system showed the highest values (90.6 ± 38.5 µm), but there was no statistical difference between Ceramill, Cerec and EDG groups.

Not only marginal adaptation is important for the longevity of the restoration, but also the internal fit. The cement space or internal fit is a uniform space that facilitates seating without compromising retention and resistance forms. This is important because all-ceramic restorations are more fragile compared to metal-ceramics and the precision of fit can influence the clinical prognosis.[37] Increasingly larger gaps are being accepted with advancements in adhesive cement technology[38], but some authors suggest that gaps should not exceed 100 µm at the occlusal surface. If cement thickness present a variation of 450 to 500 µm, the benefits of bonding are lost because of polymerization shrinkage stress.[11] Concerning axial wall, a mean width around 122 µm seems to reduce the fracture strength of the crowns.[39] Considering such information and the mean axial wall values ranging from 48 ± 26.8 µm (Ceramill) to 104.9 ± 18.3 µm (Zirkonzahn), the ceramic systems examined should be adequate for clinical use. The occlusal area showed the largest gap for all CAD-CAM systems, ranging from 111.1 ± 38.2 µm (Zirkonzahn) to 228 ± 22.57 µm (EDG). Other studies also reported differences in the restoration fit according to the measuring locations.[23,37,38,40,41] Those studies reported an increase in the mean gap values from the marginal area to axial and occlusal measuring locations, suggesting that the adaptation of CAD/CAM restorations is less accurate in the internal areas.

The differences in adaptation may be related to the quality of acquisition and processing of the digital data[42], preparation geometry, type of restoration, and dental laboratory techniques.[36,9,43-45] The internal adaptation of the CAD/CAM restorations mostly depends on milling burs size too. Details smaller than the diameter of the milling burs cannot be reproduced precisely.[42] The grinding process and the preparation design may also affect internal adaptation. Another explanation for wider internal gap is a phenomenon called "overshoot" that simulate virtual peaks near the edges.[40] Since there is no elevation of the die geometry in reality, an increase of internal discrepancy may result.

Because of the limitations presented by the replica technique, other ways of measuring the adaptation of restorations have emerged. The most recent and innovative methodology was the x-ray microtomography.[46] It has been used by several researchers[38,47-50] and cited in the systematic review of Contrepois et al[46] as the most indicated method for assessing the marginal and internal fit of dental restorations. The use of this technology has brought many improvements to adaptation studies. The digital sections enables the visualization of the cement space of the crown on the die surfaces, not only on the measurement points but also throughout the entire section.

Absolute mean values found by the micro-CT were higher than by replica technique. This might be the result of the compression of the light body silicone layer by the second layer of heavy body silicone. Nevertheless, there were two regions where this explanation cannot be applied.

Despite this difference between techniques, the values found with micro-CT are also within the clinically acceptable. For a minimum difference the lowest absolute mean for the marginal adaptation was found in EDG group (91.8 ± 45.1 µm), followed by Zirkonzahn (92.5 ± 30.7 µm) and Cerec (103.6 ± 43.2 µm), although they do not show statistically significant differences between them. Ceramill group presented the highest absolute mean (133.0 ± 71.5 µm), statistically similar to the Cerec group.

Regarding the internal adaptation, the values followed the pattern already discussed. The axial values were higher than the marginal values and occlusal values were higher than the others, excepted for Zirkonzahn group. According to the replica technique, Ceramill group (92.2 ± 36.8 µm) showed the lowest absolute mean for axial region, statistically similar to the EDG group (94.2 ± 42.7 µm), followed by the Cerec (161.2 ± 67.6 µm) and Zirkonzahn (170.1 ±

38.2 µm) groups, also statistically similar to each other. For occlusal values exceptions can be observed to the trend of micro-CT values being larger than the replica technique. Ceramill and EDG groups presented lower absolute mean values in the evaluation by micro-CT than in replica evaluations. The lowest absolute mean for the occlusal region was for the Ceramill group (119.0 ± 76.1 µm) followed by Zirkonzahn (148.0 ± 35.5 µm), EDG (201.2 ± 72.3 µm) and Cerec (229.4 ± 49.0 µm) groups.

Comparing the adaptation through different methodologies becomes unavoidable. However, direct comparisons with 2-dimensional measurements made from physical sections should be made with caution because of the differences of physical and digital images.[51] For an specific region of a specimen, 28 measurements were taken by the micro-CT technique and 8 measurements for the replica technique. Because of this variation and following a methodological concerning, the average of the measures were considered in Pearson's correlation coefficient test. A strong correlation was found between the methods ($p= 0.01$ and $r= 0.69$), which shows a pairing between the techniques.

This study proposes the observation data of the internal fit of crowns through proportion between the occlusal and axial regions called uniformity index (UI). The UI describes how uniform is the internal space: the closer the ratio is to 1 the more uniform the internal space is. Data was arranged separately for the different methodologies (Graphics 1 and 2). In general, the variability of the replica technique was lower than for micro-CT. However, for both analysis the Zirkonzahn group showed the UI closest to ideal, i.e., internal spacing is more uniform. Cerec, EDG and Ceramill respectively followed it, in both measuring techniques. This form of assessment provides an analysis not only in absolute terms, but also according to the distribution of the internal space. As important as presenting values within clinically acceptable levels it is important to evaluate the distribution of space, responsible for proper flow of cement, proper dissipation of occlusal forces and for decreasing the shear stress at the interface of the restoration, which can exceed the bond strength and lead to failure of the bond or ceramic fracture.[35]

Although there is no control group in the present investigation, results from other studies suggested that restorations produced by CAD/CAM technology presented similar gap dimensions to metal–ceramic systems[38,40,52] It is important to highlight that the ceramic material is not the main study element but it was carefully selected, taking into account factors such as popularity of the system, minimal volume variation after crystallization, the combination of adequate strength and favorable optical properties, among others.

Controlled clinical studies are considered the gold standard for evaluating the performance of biomaterials and design aspects of dental prostheses. However, these studies are extremely costly and other variables compromise the individual interpretation of the study object.[53] Thus, in vitro studies show positive aspects providing standardized conditions with respect to preparation design, impression technique, operator and provide the evaluation of individual variables acting in the marginal adaptation[54], in case of this study the CAD-CAM system. Although this study did not replace clinical studies, because their results may be different clinical situations, and clinical trials should be conducted in the future with different CAD-CAM systems.

Other studies have evaluated the adaptation of different CAD-CAM systems[40,37,55-60], however none resembles the combination of methodologies and the variety of data presented in this study. Performed the relevant analysis, it can be stated that the different systems considered here offered satisfactory marginal adaptation and internal fit and can well compete with conventional restorations. Furthermore, both techniques are effective for measuring marginal and internal space, confirming the hypothesis of the study.

CONCLUSIONS

Within the limitations of the in vitro study, it was concluded that the marginal adaptation and internal fit of monolithic lithium disilicate crowns produced by the four CAD-CAM systems are within clinically acceptable levels. Replica technique and micro-CT methodologies are appropriate to assess marginal adaptation and internal fit, presenting a strong correlation between the methods ($p= 0.01$ and $r= 0.69$). Zirkonzahn group showed the most uniform distribuition of internal space in both techniques of measurement. Future in vivo studies should evaluate the adaptation and clinical performance of crowns made from different CAD-CAM systems.

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LEGENDS FOR ILLUSTRATIONS

Figure 1 - Prepared tooth included in acrylic base.

Figure 2 - Lithium disilicate glass-ceramic crowns.

Figure 3 - Cementation with a light body silicone.

Figure 4 - Charge device applying 50N load.

Figure 5 - Pellicle of silicone positioned at the prepared tooth after removing the crown.

Figure 6 - SkyScan DataViewer 1.5.1.2 software: coronal (x-z plane), sagittal (y-z plane), and transaxial (x-y plane) views.

Figure 7 - Device to standardize the positioning to replica technique.

Figure 8 - Included film thickness in heavy body silicone.

Figure 9 - Completing with heavy body silicone to conclude the inclusion of film thickness.

Figure 10 - Cutting and selection of areas to be examined by the replica technique.

Figure 11 - Crown center located in CTAn software to provide the selection of testing slices.

Figure 12 - Scheme of slices chosen for testing.

Figure 13 - Measurement places of light body silicone film thickness: marginal (cervical), axial (middle of the axial wall) and occlusal (middle of the half of the occlusal surface studied).

Figure 14 - Uniformity Index (UI) from micro-CT analysis.

Figure 15 - Uniformity Index (UI) from replica technique analysis.

Fig 1


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for CEREC® and inLab®
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Fig 2

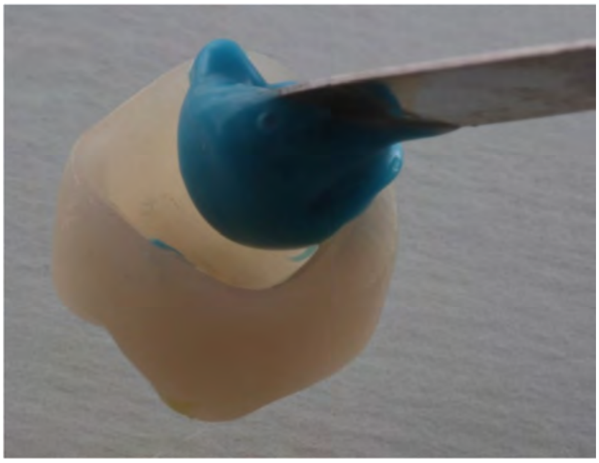

Fig 3

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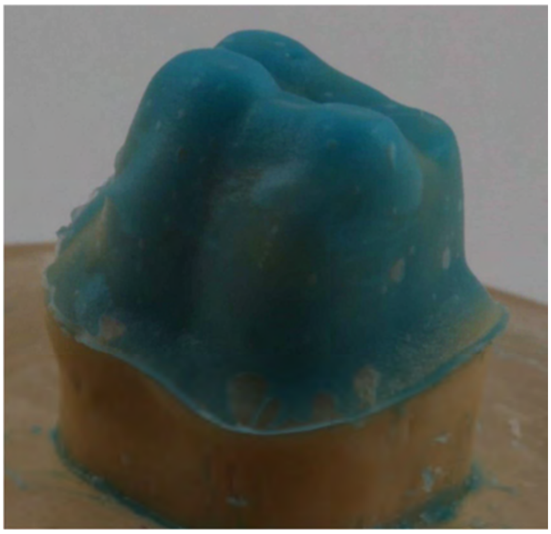

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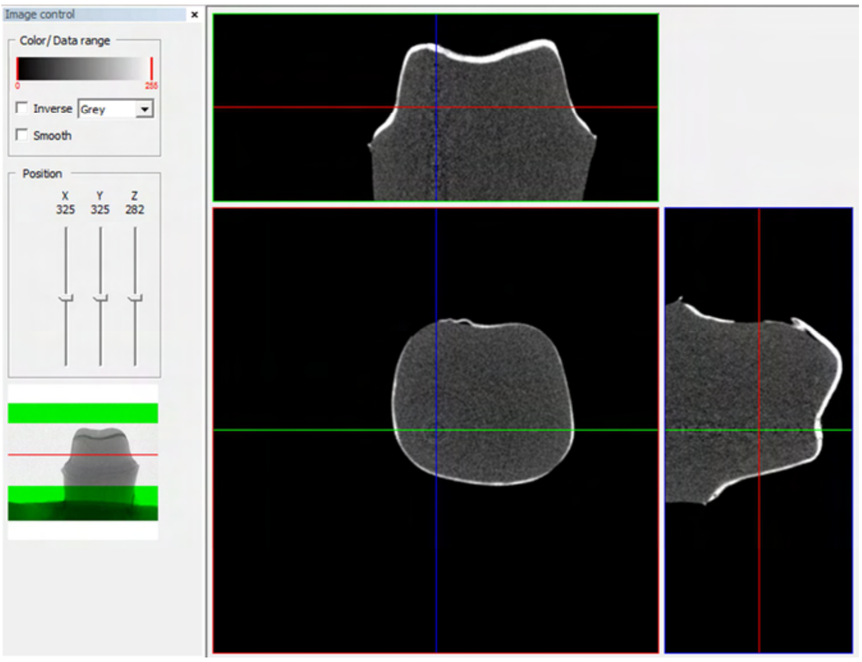
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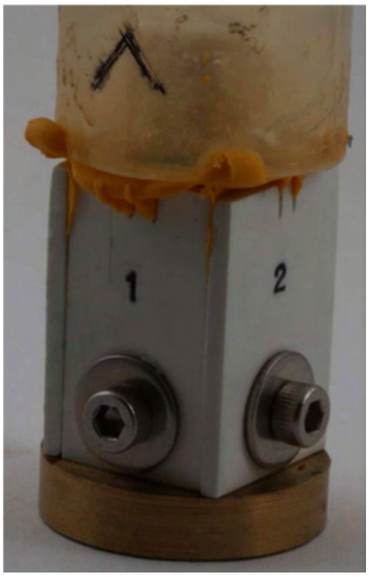

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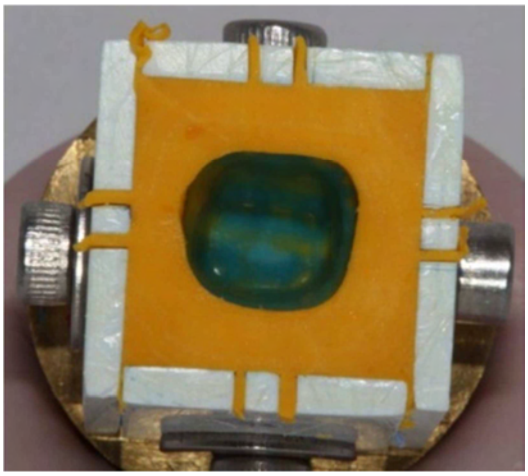

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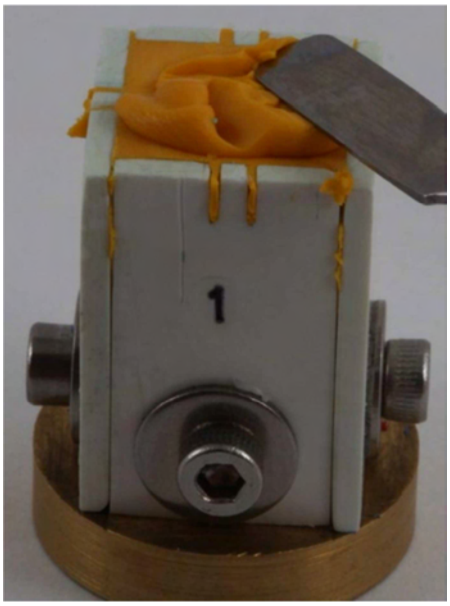

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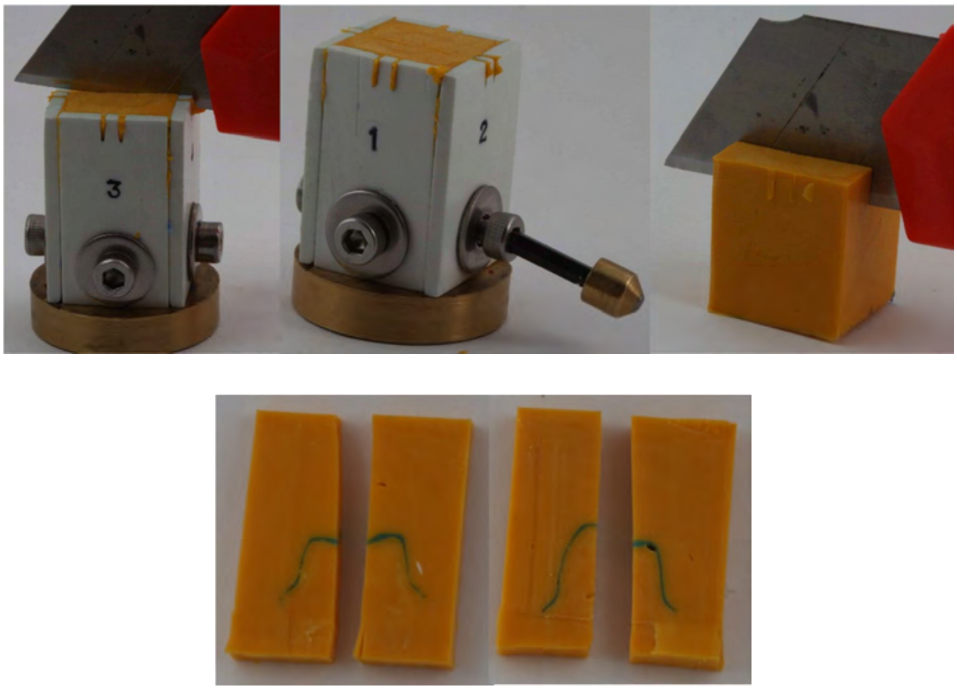

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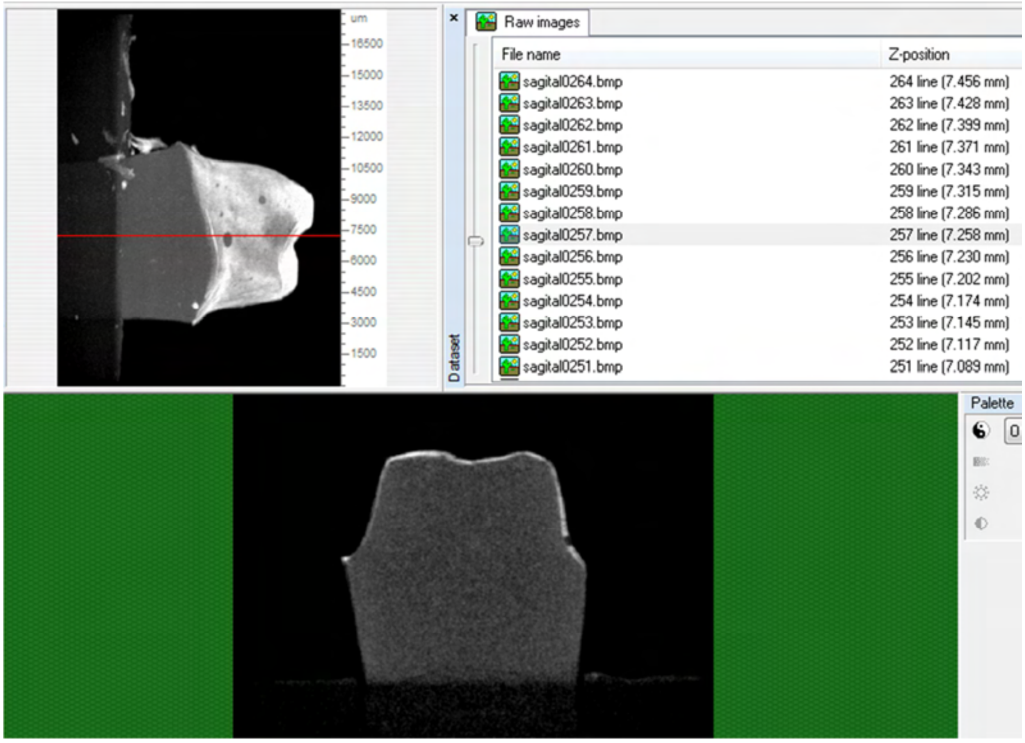
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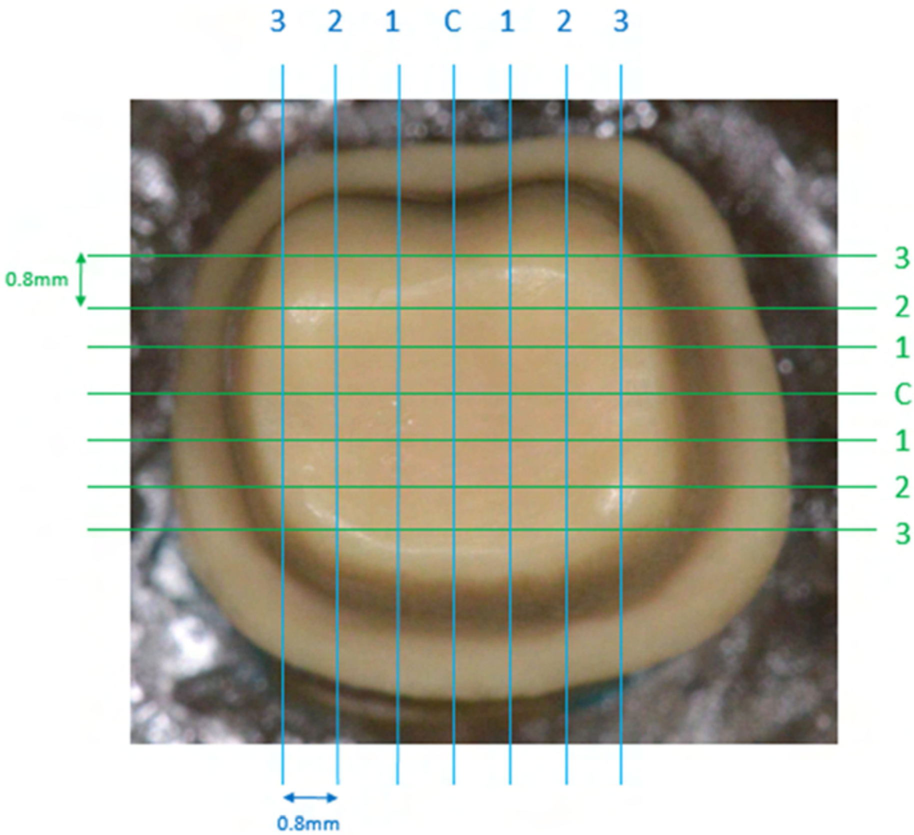
Fig 11



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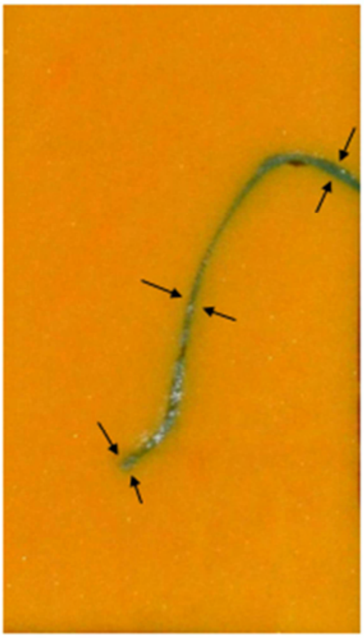

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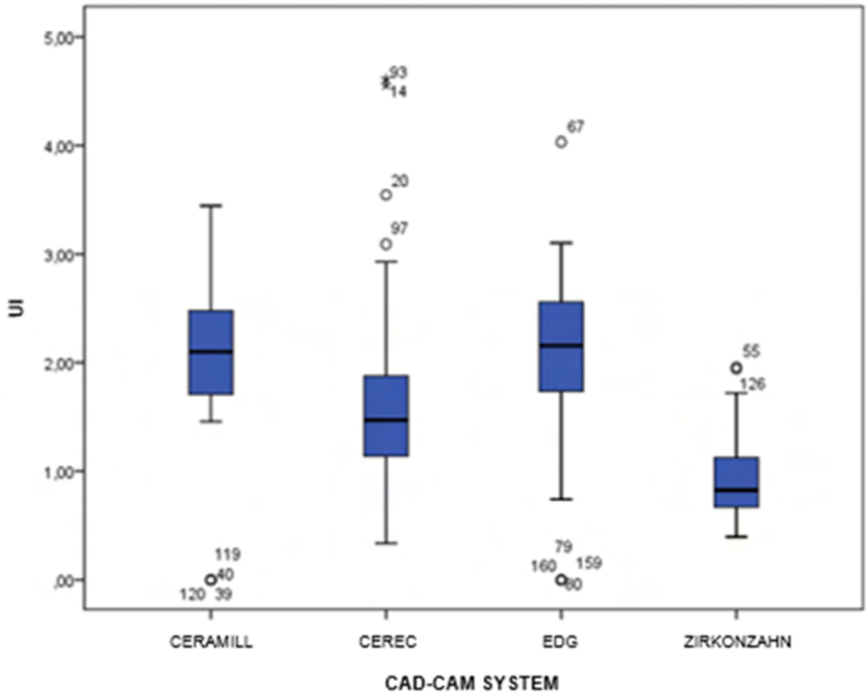
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CERAMILL
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EDG
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CAD-CAM SYSTEM

Fig 14

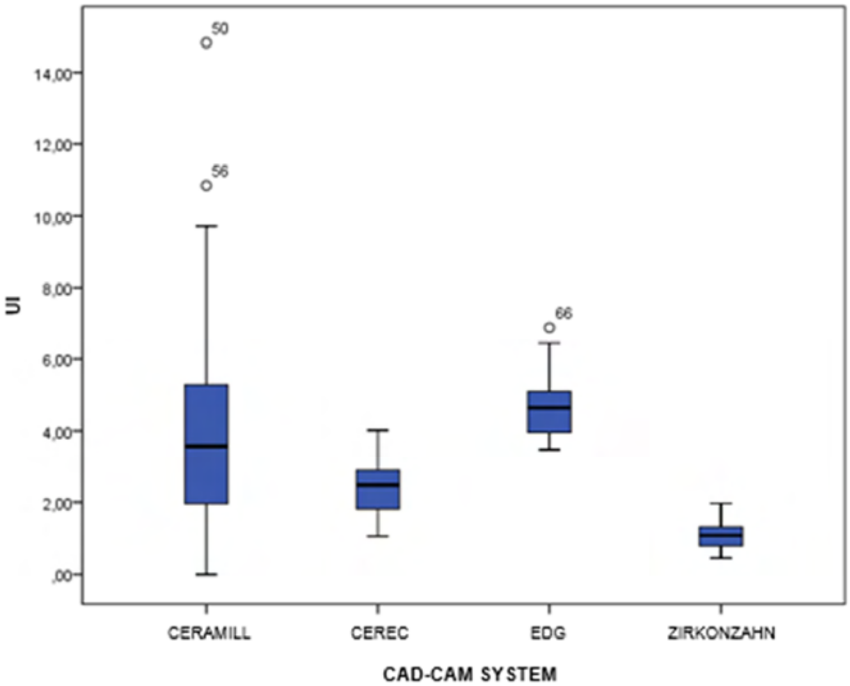
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Fig 15

Table 1. Adaptation analysis using micro-CT.

CAD/CAM SYSTEM	FIT PARAMETERS		
	MARGINAL FIT	INTERNAL FIT	
		Axial	Occlusal
CERAMILL	133,0 ± 71,5 $^{b, c, A}$	92,2 ± 36,8 $^{a, A}$	119,0 ± 76,1 $^{d, e, f, A}$
CEREC	103,6 ± 43,2 $^{a, c, A}$	161,2 ± 67,6 $^{b, d, A}$	229,4 ± 49,0 $^{f, A}$
EDG	91,8 ± 45,1 $^{a, A}$	94,2 ± 42,7 $^{a, c, A}$	201,2 ± 72,3 $^{e, f, A}$
ZIRKONZAHAN	92,5 ± 30,7 $^{a, A}$	170,1 ± 38,2 $^{b, d, e, A}$	148,0 ± 35,5 $^{b, A}$

Means with the same superscript letter are not significantly different using post hoc Tukey honestly significant difference test (P>.05). There was no difference between the cuts, which is represented by the capital letter.

Table 2. Adaptation analysis using replica technique.

CAD/CAM SYSTEM	FIT PARAMETERS		
	MARGINAL FIT	INTERNAL FIT	
		Axial	Occlusal
CERAMILL	$90{,}6 \pm 38{,}5^{b, c, d, A}$	$48{,}0 \pm 26{,}8^{a, A}$	$180{,}0 \pm 82{,}0^{e, A}$
CEREC	$60{,}7 \pm 15{,}4^{a, b, A}$	$85{,}2 \pm 18{,}7^{a, b, c, d, A}$	$196{,}5 \pm 58{,}1^{e, f, A}$
EDG	$68{,}0 \pm 16{,}7^{a, b, c, A}$	$50{,}0 \pm 10{,}2^{a, A}$	$228{,}0 \pm 22{,}57^{f, A}$
ZIRKONZAHAN	$48{,}2 \pm 19{,}6^{a, A}$	$104{,}9 \pm 18{,}3^{c, d, A}$	$111{,}1 \pm 38{,}2^{d, A}$

Means with the same superscript letter are not significantly different using post hoc Tukey honestly significant difference test (P>.05). There was no difference between the cuts, which is represented by the capital letter.

3 Discussion

3 DISCUSSION

Marginal adaptation and internal fit are considered the most important criteria for the longevity of all-ceramic crowns.[44] Until the late 1980s, investigators who evaluated marginal fit not always measured the same distances.[45] Holmes et al[46] proposed a clear terminology in 1989 by which marginal fit is generally evaluated by measuring the marginal gap or the absolute marginal discrepancy.[46,47] Most of the previous studies on marginal fit was done using replica technique[48] and this methodology is well established in the literature. Examination with a silicone indicator does not destroy the restoration. However, this method have some limitations: the fit is measured at predefined points on each crown, which might not represent the overall accuracy[2,949]; indirect data acquisition[43,50] and also some errors during replication could occur, once very tight adaptations can lacerate the pellicle[51]; and difficulties with the specimen sectioning[22,52].

In order to reduce the limitations, it has been proposed in this study the use of a device for standardization of the replica technique (Fig. 8). The inclusion of the light body silicone pellicle in a matrix of heavy body silicone in a standardized way, favored the slices made and consequently standardized the samples for posterior analysis.

The measurements were performed at the marginal, axial and occlusal regions of each slice of the vestibular, mesial, distal and lingual tooth surfaces.[48] Previous studies revealed that no statistical difference exists between the measurements according to the tooth surfaces.[2] Therefore, data were grouped into regions in order to clarify the interpretation.

An acceptable marginal fit has been suggested as a maximum of 120 μm [35] in most studies, whereas others have been reported a range from 50 to 150 μm.[36] Boitelle et al.[2] in a recent systematic review reported that from 26 articles dealing with the adaptation of single crowns, the marginal adaptation ranged from 9.94 ± 4.18 μm to 308 ± 92 μm, but most studies have shown less than 80 μm. The medians of all four systems tested in the present study were in accordance with the average found in the literature and within clinically acceptable. Considering absolute values, the Zirkonzahn group presented lower values for marginal fit (48.2 ± 19.6 μm).

However, there was no statistical difference between Zirkonzahn, EDG and Cerec groups. Performing the same analysis inversely, the Ceramill system showed the highest values (90.6 ± 38.5 μm), but there was no statistical difference between Ceramill, Cerec and EDG groups.

Not only marginal adaptation is important for the longevity of the restoration, but also the internal fit. The cement space or internal fit is a uniform space that facilitates seating without compromising retention and resistance forms. This is important because all-ceramic restorations are more fragile compared to metal-ceramics and the precision of fit can influence the clinical prognosis.[53] Increasingly larger gaps are being accepted with advancements in adhesive cement technology[54], but some authors suggest that gaps should not exceed 100 μm at the occlusal surface. If cement thickness present a variation of 450 to 500 μm, the benefits of bonding are lost because of polymerization shrinkage stress.[32] Concerning axial wall, a mean width around 122 μm seems to reduce the fracture strength of the crowns.[55]

Considering such information and the mean axial wall values ranging from 48 ± 26.8 μm (Ceramill) to 104.9 ± 18.3 μm (Zirkonzahn), the ceramic systems examined should be adequate for clinical use. The occlusal area showed the largest gap for all CAD-CAM systems, ranging from 111.1 ± 38.2 μm (Zirkonzahn) to 228 ± 22.57 μm (EDG). Other studies also reported differences in the restoration fit according to the measuring locations.[43,53,54,56,57] Those studies reported an increase in the mean gap values from the marginal area to axial and occlusal measuring locations, suggesting that the adaptation of CAD/CAM restorations is less accurate in the internal areas.

The differences in adaptation may be related to the quality of acquisition and processing of the digital data[58], preparation geometry, type of restoration, and dental laboratory techniques.[40,52,59-61] The internal adaptation of the CAD/CAM restorations mostly depends on milling burs size too. Details smaller than the diameter of the milling burs cannot be reproduced precisely.[58] The grinding process and the preparation design may also affect internal adaptation. The narrowest possible diameter of the preparation is determined by the smallest diameter of the bur used for machining the internal surface. Thus, in structures smaller than the narrowest bur diameter, more internal substance may be removed than necessary. This may also result in larger internal gaps than necessary for a good fit.[58,62] Another explanation for wider internal gap is a phenomenon called "overshoot" that simulate virtual peaks near the edges.[56] Since there is no elevation of the die geometry in reality, an increase of internal discrepancy may result.

Because of the limitations presented by the replica technique, other ways of measuring the adaptation of restorations have emerged. Direct microscopy observation, cross-sectioning of cemented specimens, laser videography and perfilometry are some examples of methodologies. The most recent and innovative methodology was the x-ray microtomography.[45] It is a non-destructive method of analysis that allows high resolution investigation of the internal gap between tooth preparation and the restoration and is the only method that allows both a precise identification of the critical distances and a sufficient number of gap measurements. Micro-CT technology has been used by several researchers[47,63-66] and cited in the systematic review of Contrepois et al[45] as the most indicated method for assessing the marginal and internal fit of dental restorations. The use of this technology has brought many improvements to adaptation studies. The digital sections enables the visualization of the cement space of the crown on the die surfaces, not only on the measurement points but also throughout the entire section.

Although the use of such sophisticated software allowed 3-dimensional measurements, 2-dimensional sections were used to facilitate the visualization and to compare the results with previous studies. Eighty-four measurements were taken for each specimen. This clearly reflects a satisfactory utilization of larger amount of data provided by this technology. There is no agreement in the literature concerning the number of measurement sites necessary to evaluate marginal fit. Yet, this parameter seems critical because, within a lateral distance of 300 µm, the marginal opening can fluctuate by 100 µm on the same specimen.[67] Groten et al[68] suggested taking 50 measurements of the marginal fit, but there is a wide divergence on the subject.[45] In this study, it was preferred to take full advantage of the information brought by scanning, culminating in a high number of measurements per specimen.

Absolute mean values found by the micro-CT were higher than by replica technique. This might be the result of the compression of the light body silicone layer by the second layer of heavy body silicone. Nevertheless, there were two regions where this explanation cannot be applied.

Despite this difference between techniques, the values found with micro-CT are also within the clinically acceptable. For a minimum difference the lowest absolute mean for the marginal adaptation was found in EDG group (91.8 ± 45.1

μm), followed by Zirkonzahn (92.5 ± 30.7 μm) and Cerec (103.6 ± 43.2 μm), although they do not show statistically significant differences between them. Ceramill group presented the highest absolute mean (133.0 ± 71.5 μm), statistically similar to the Cerec group.

Regarding the internal adaptation, the values followed the pattern already discussed. The axial values were higher than the marginal values and occlusal values were higher than the others, excepted for Zirkonzahn group. According to the replica technique, Ceramill group (92.2 ± 36.8 μm) showed the lowest absolute mean for axial region, statistically similar to the EDG group (94.2 ± 42.7 μm), followed by the Cerec (161.2 ± 67.6 μm) and Zirkonzahn (170.1 ± 38.2 μm) groups, also statistically similar to each other. For occlusal values exceptions can be observed to the trend of micro-CT values being larger than the replica technique. Ceramill and EDG groups presented lower absolute mean values in the evaluation by micro-CT than in replica evaluations. The lowest absolute mean for the occlusal region was for the Ceramill group (119.0 ± 76.1 μm) followed by Zirkonzahn (148.0 ± 35.5 μm), EDG (201.2 ± 72.3 μm) and Cerec (229.4 ± 49.0 μm) groups.

Comparing the adaptation through different methodologies becomes unavoidable. However, direct comparisons with 2-dimensional measurements made from physical sections should be made with caution because of the differences of physical and digital images.[69] For an specific region of a specimen, 28 measurements were taken by the micro-CT technique and 8 measurements for the replica technique. Because of this variation and following a methodological concerning, the average of the measures were considered in Pearson's correlation coefficient test. A strong correlation was found between the methods (p= 0.01 and r= 0.69), which shows a pairing between the techniques.

This study proposes the observation data of the internal fit of crowns through proportion between the occlusal and axial regions called uniformity index (UI). The UI describes how uniform is the internal space: the closer the ratio is to 1 the more uniform the internal space is. Data was arranged separately for the different methodologies (Graphics 1 and 2). In general, the variability of the replica technique was lower than for micro-CT. However, for both analysis the Zirkonzahn group showed the UI closest to ideal, i.e., internal spacing is more uniform. Cerec, EDG and Ceramill respectively followed it, in both measuring techniques. This form of assessment provides an analysis not only in absolute terms, but also according to the distribution of the internal space. As important as presenting values within clinically acceptable levels it is important to evaluate the distribution of space, responsible for proper flow of cement, proper dissipation of occlusal forces and for decreasing the shear stress at the interface of the restoration, which can exceed the bond strength and lead to failure of the bond or ceramic fracture.[9]

Although there is no control group in the present investigation, results from other studies suggested that restorations produced by CAD/CAM technology presented similar gap dimensions to metal–ceramic systems.[54,56,70] It is important to highlight that the ceramic material is not the main study element but it was carefully selected, taking into account factors such as popularity of the system, minimal volume variation after crystallization, the combination of adequate strength and favorable optical properties, among others.

Controlled clinical studies are considered the gold standard for evaluating the performance of biomaterials and design aspects of dental prostheses. However, these studies are extremely costly and other variables compromise the individual interpretation of the study object.[71] Thus, in vitro studies show positive aspects providing standardized conditions with respect to preparation design, impression technique, operator and provide the evaluation of individual variables acting in the marginal adaptation[72], in case of this study the CAD-CAM system. Although this study did not replace clinical studies, because their results may be different clinical situations, and clinical trials should be conducted in the future with different CAD-CAM systems.

Other studies have evaluated the adaptation of different CAD-CAM systems[19,56,73-78], however none resembles the combination of methodologies and the variety of data presented in this study. Performed the relevant analysis, it can be stated that the different systems considered here offered satisfactory marginal adaptation and internal fit and can well compete with conventional restorations. Furthermore, both techniques are effective for measuring marginal and internal space, confirming the hypothesis of the study.

4 Final Considerations

4 FINAL CONSIDERATIONS

Within the limitations of the in vitro study, it was concluded that the marginal adaptation and internal fit of monolithic lithium disilicate crowns produced by the four CAD-CAM systems are within clinically acceptable levels. Replica technique and micro-CT methodologies are appropriate to assess marginal adaptation and internal fit, presenting a strong correlation between the methods ($p= 0.01$ and $r= 0.69$). Zirkonzahn group showed the most uniform distribuition of internal space in both techniques of measurement. Future in vivo studies should evaluate the adaptation and clinical performance of crowns made from different CAD-CAM systems.

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Annexes

ANNEX A – Guidelines for The Journal of Prosthetic Dentistry:

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Tables should be self-explanatory and should supplement, not duplicate the text. Provide all tables at the end of the manuscript after the reference list and before the Figures. There should be only one table per page. Omit internal horizontal and vertical rules (lines). Omit any shading or color.Do not list tables in parts (Table Ia, Ib, etc.). Each should have its own number. Number the tables in the order in which they are mentioned in the text (Table 1., Table 2, etc).Supply a concise legend that describes the content of the table. Create descriptive column and row headings. Within columns, align data such that decimal points may be traced in a straight line. Use decimal points (periods), not commas, to mark places past the integer (eg, 3.5 rather than 3,5).In a line beneath the table, define any abbreviations used in the table.If a table (or any data within it) was published previously, give full credit to the original source in a footnote to the table. If necessary, obtain permission to reprint from the author/publisher.The tables should be submitted in Microsoft Word. If a table has been prepared in Excel, it should be imported into the manuscript.

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